Space-based interferometric telescopes for the far infrared

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ABSTRACT

We discuss concepts for deploying direct detection interferometers in space which are optimized for the wavelength range $40\,\mu$m to $500\,\mu$m. In particular, we introduce two missions in NASA's current strategic plan: SPIRIT (SPace InfraRed Interferometric Telescope) and SPECS (Submillimeter Probe of the Evolution of Cosmic Structure).

Passive cooling through a large multi-layered sunshield, cryogenic optics, background limited detectors, and angular resolution comparable to that of a single 50 meter aperture gives SPIRIT a spectacular combination of sensitivity and angular resolution in the far infrared (FIR). In our strawman mission design which could be ready for launch by 2010, multiple, cold, membrane mirrors are arranged along two deployable booms. The entire structure rotates, giving SPIRIT good u-v coverage and the ability to make high dynamic range synthesis images. SPECS is an even larger scale FIR/submm direct detection interferometer. Separated free-flying (or tethered) outrigger mirrors allow a maximum baseline of ~1 km. The combination of extremely good spatial resolution, passive and active cooling of the optics, and background limited detectors will allow sensitive imaging well below the confusion limit in the FIR. SPECS is to be launched in the decade following SPIRIT.

Both SPIRIT and SPECS operate in a long-stroke Michelson beam combination mode to enable simultaneous imaging over a field size of at least 9 subaperture diffraction spots with spectral resolution of order 1000. An on-demand spectral resolving element could further increase spectral resolution to of order 10^5 for specific science objectives and for maintaining background limited operation when observing bright objects.

A primary science goal for SPIRIT and SPECS is to probe the structure of the early Universe; these missions directly address grand challenge questions regarding the formation of galaxies and the role of star formation in galaxy evolution. In addition, these facilities provide powerful tools for studying the local ISM and the star formation and planet formation processes. SPIRIT and SPECS would be part of NASA's complement of space-based interferometers such as SIM (Space Interferometer Mission), TPF (Terestrial Planet Finder), and PI (Planet Imager).

Keywords: Interferometers, IR telescopes, Space telescopes, Cryogenic optics, Membrane mirrors

1. INTRODUCTION

Far infrared (FIR) radiation from $40\,\mu$m to $500\,\mu$m is critical for quantitatively probing the conditions of the diffuse gas in galaxies and proto-galaxies. After the formation and subsequent mass loss from (and/or explosions of) the first generation of stars, the "population III" stars, heavy elements such as C, N, O, ... are present in the Universe. These heavy elements will be in the form of solid particles ("dust"), in atomic or ionic form, or in molecules and therefore capable of emitting prolifically in the FIR. Prior to the formation of population III stars one can expect the lowest transitions of H_2 at $28.2\,\mu$m and $17\,\mu$m and HD at $112\,\mu$m, $56.2\,\mu$m, and $37.7\,\mu$m to contribute significantly to the cooling of protogalactic condensations. We do not know exactly when and how population III stars were formed, but we strongly suspect that this occurred sometime in the redshift range $z = 5$ to $z = 20$ and that H_2/HD cooling played a prominent role. Several of the above mentioned lines, necessary for our understanding of how initial condensations formed, are redshifted into the FIR.

The presence of dust has important observational consequences for our studies of how galaxies form and evolve. Dust obscures our view of the densest regions of galaxies, the central nuclei and regions of intense star formation, from the mid-IR to the soft X-ray regime. Absorption of these photons heats the dust; the dust reradiates this energy in the FIR. In our own Milky Way Galaxy, for example, approximately one half of the observed total luminosity has been reradiated by the dust and lies in the spectral region $40\,\mu m$ to $500\,\mu m$. Based on their JCMT/SCUBA observations and the measured COBE FIR/submillimeter background, Barger and Cowie[1] postulate the existence of a hitherto unnoticed population of luminous infrared galaxies in the redshift interval $z \approx 1-3$ undergoing intense star formation. Indeed, the peak of dust continuum emission lies in the FIR out to redshifts of $z \sim 5$. Moreover, many important molecular and fine structure lines (e.g. HD, H_2O, HDO, fs lines of the most abundant elements, high-J CO, bending modes of large, complex molecules) are present in this wavelength range for $z \lesssim 5$ and — although unobscured by the presence of cosmic dust — are inaccessible from the ground. With the rapid development of technologies critical for the FIR, we are able to consider construction of much improved observing facilities for this spectral regime.

FIRST (Far InfraRed Space Telescope) will begin to observe in the FIR after its launch in 2007. Passively cooled to about 80K, FIRST will be more sensitive than the Stratospheric Observatory for Far Infrared Astronomy (SOFIA), and because of its aperture size (3.5m) it will have 6 times better spatial resolution (7 arcsec at $100\,\mu m$) than the Infrared Satelite Observatory (ISO) had. This combination of sensitivity and resolution will permit FIRST to address many important science issues in the FIR. Still, given the typical sizes and separations of galaxies at redshifts $z \gtrsim 1$ and the typical sizes of and distances to nearby protoplanetary disks and jets, many questions regarding the origin of cosmic structure, the history of star formation in the early Universe and the formation of stars and planets require even higher sensitivity and greater angular resolution than are possible with either SOFIA or FIRST.[2] These can only be achieved by a large scale, space based FIR telescope operating at cryogenic temperatures. Currently, two types of missions are being considered for these objectives: 1) a large (~25m), cooled ($T \lesssim 10$K) filled aperture infrared telescope (FAIR) and 2) long baseline, cooled interferometers: SPIRIT (~40m baseline on trussed booms) and SPECS (~1 km baseline multiple spacecraft interferometer). Discussion of the cooled interferometers is the subject of this paper, although several aspects (in particular: vibrationless cooling, advanced FIR detectors) are common to both types of missions.

It is envisioned that SPIRIT is launched in 2010 and SPECS in the following decade.

2. MISSION CONCEPTS

2.1. SPace InfraRed Interferometric Telescope

SPIRIT is based on a low mass, deployable structures concept; a pair of 20 meter class trussed booms will be deployed from a central platform. We have considered several alternate designs which allow the multiple baselines necessary for full image reconstruction, but our preliminary studies can by no means be deemed exhaustive. For example, the booms could be extended or retracted during an observation or two subaperture flats could travel along tracks on fixed, fully extended booms. Alternatively, the booms could support several subaperture 3 meter flats, strategically placed to optimize u-v coverage (see Fig. 1), whereby the maximum separation of the subapertures would be approximately 40 meters. We currently envision the flats as tensioned membrane optics. A pair of two-gimbal, steerable relay flats mounted on a mast select the pair of outrigger flats on the booms to be deflected into the 10:1 beam compressing optics. Several of the boom-mounted flats would also require some degree of one-axis steerable tilting in order to deflect light into the correct relay flat.

In this wavelength regime, cooling the instrument optics to a few Kelvin enables dramatic gains in sensitivity up to the limits given by the zodical emission at 1 AU. Both the membrane flats and subsequent optics would be cooled to a few Kelvin in SPIRIT; our off-axis design allows use of somewhat warmer support structure (30K) which lies outside of the optical path. We envision using only reflective optics in the system which simplify cooling of the optics as well as enabling a wide range of wavelengths. Upon exiting the beam compressors, the light is directed into delay lines. For optimal u-v coverage, we employ selectable static delay lines to compensate for gross path length compensation. Active delay lines then provide of order 1 meter of optical delay for fringe tracking and spectral scanning. This combination of active and static delay lines is used in the Keck Interferometer[3,4] Relay optics then transport the beams from the delay lines to optics for Michaelson beam combination, spatial filtering, and spectral filtering, although the exact ordering of these functions has yet to be determined.

Our goal is for the focal plane to be single mode sky background limited. In addition to a sophisticated optical system, this requires broad band detectors with high sensitivity to be discussed in greater detail in §3. We envision a TES[6] bolometer focal plane array with NEPs of order 10^{-20} W $Hz^{-1/2}$; large formats would be enabled using the PUD fabrication technique developed at GSFC or arrays of spider web bolometers[7] developed at JPL (see Fig. 4).

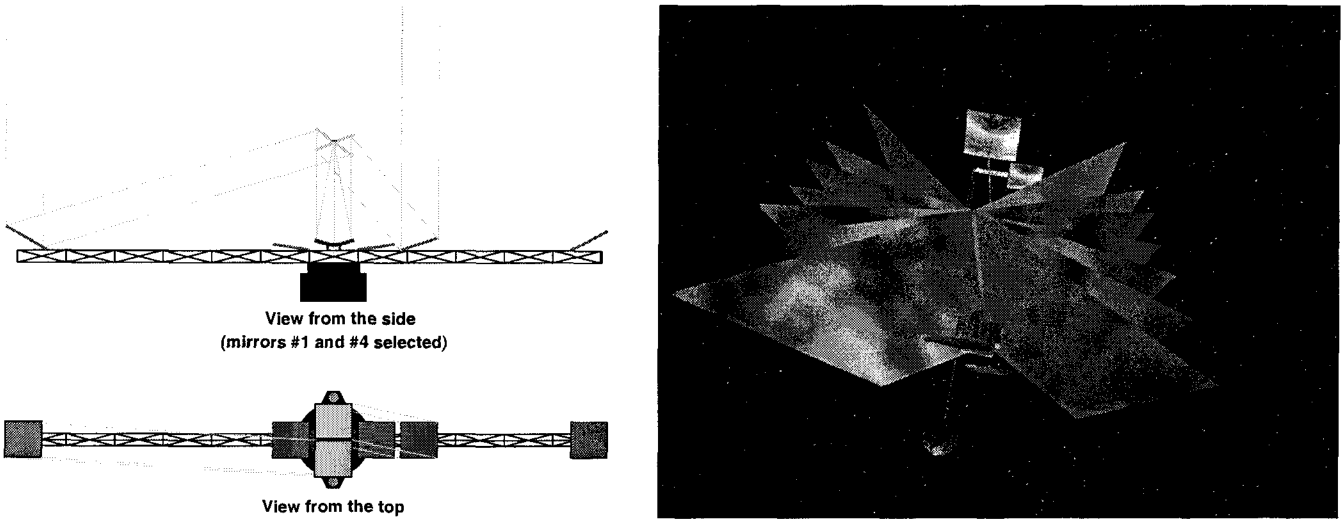

Figure 1. **Left**: SPIRIT (without sunshield). Due to the placement of the five subaperture outrigger flat mirrors along the booms (at positions $x = -7, -1, +1, +2, +6$ units), there are a total of 10 possible baselines: 1, 2, 3, 4, 5, 6, 7, 8, 9, and 13 units. Thus, with the scale factor 1 unit = 3m currently under consideration, complete and uniform u-v coverage up to a baseline of 27m is possible, with additional high spatial frequency information being provided by the 39m baseline. **Right**: The trussed boom and mirrors construction (top of figure, mostly obscurred) is located behind a multiply layered sunshield. The sunny (warm) side of SPIRIT's sunshield is at the bottom of this figure, where the solar panels, communications antenna, warm electronics, cooling radiators, and other heat producing components are located.

Development of MUXs capable reading out bolometer arrays without imposing large heat load or fabrication penalties is currently underway at GSFC and NIST. Large format bolometer arrays (100 × 100) would permit operation of SPIRIT in a wide field Michelson Mode for simultaneous spatial-spectral imaging.

Wide field Michelson Interferometry is a standard Michelson stellar interferometer where the interfering beams are combined at a beam splitter, as shown in Fig. 2. But instead of a single detector to detect the interference of the starlight from the two apertures, there is an imaging spectrometer.

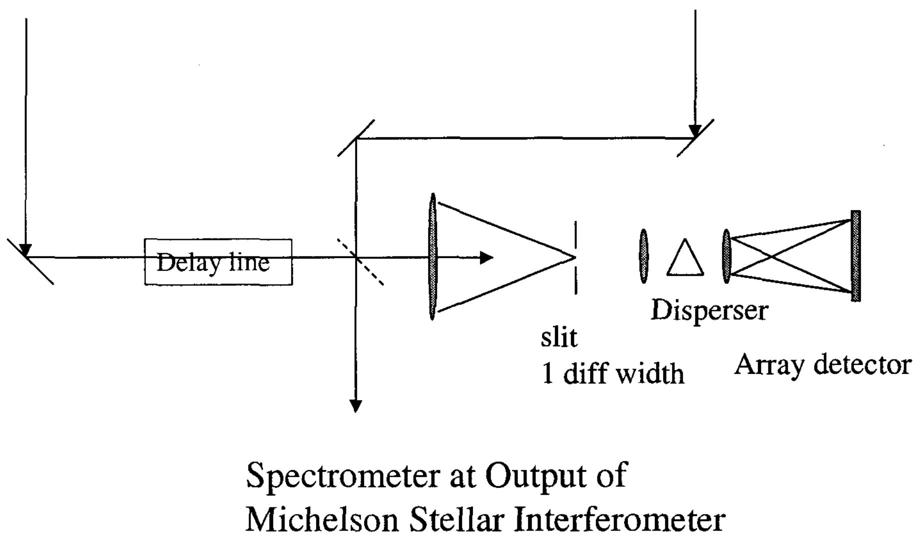

Figure 2. Schematic view of a long stroke Michelson Interferometer, showing the spectrometer behind the michelson beam splitter

The goal is to produce an image over a field of view that is much larger than the diffraction limit of a subaperture of the interferometer. In order to see high contrast fringes over a large field of view, the imaging spectrometer has to have sufficient resolution to avoid bandwidth smearing: $\lambda/\delta\lambda \sim$ FOV/res, where 'FOV' is the imaging field of view and 'res' is λ/Baseline, the resolution of the synthetic aperture.

For maximum SNR, the imaging spectrometer will utilize detectors that are background limited at the spectral dispersion needed for wide field imaging. Ideally, the resolution of the dispersive spectrometer is high enough so that the system is detector noise limited. For higher spectral resolution, it is possible to scan the delay line. At zero optical path difference (zero to the center of the FOV), an interferometer measures the two dimension transform of the spatial distribution of the source. If at each u-v point, the delay line is scanned in w, then the spatial-spectral image $I(x, y, \lambda)$ is the three dimensional transform of the interferometer output $O(u, v, w = \text{delay})$.

The technique outlined above enables imaging a relatively large FOV while simultaneously obtaining spectral information. The basic technique of spatial-spectral imaging will be demonstrated on the SIM mission. SPIRIT and SPECs takes this concept one step further by widening the FOV beyond a single diffraction limited beam of the subaperture.

A necessary requirement on the structure is that it must be phase stable during the delay line stroke; stable to $\sim \lambda/100$, or $\sim 0.4\,\mu$m during a scan of the fast delay line. Coherent integration requires this stability to be extended for the duration of the observation to avoid time average smearing. Since coherent integration is necessary to meet the science requirements for sensitivity, stabilization of the OPD is required. It is impractical to make the structure rigid enough to meet our OPD stability requirements. Instead, we envision phase referencing the science target to a bright calibrator target. This would be done by separately observing the science target and calibrator target with two identical interferometers which share the same primary optics. The error signal from the interferometer observing the calibrator is "fed forward" to the interferometer observing the science target. Separation of the calibrator and science target is accomplished in the focal plane by a "dual star module" (DSM)[8]; pathlength feedforward has been used successfully at PTI[9] and will be used on the Keck Interferometer[4] and SIM.[5]

SPIRIT would be launched into an Earth-trailing orbit or deployed at the Lagrange point L2. There are advantages and disadvantages of each alternative which have to be addressed in future trade studies.

2.2. Submillimeter Probe of the Evolution of Cosmic Structure

Conceptually, SPECS would have many attributes in common with SPIRIT, the main distinguishing feature being a 250-fold increase in the maximum baseline length and a proportional gain in angular resolution. Separated spacecraft would be flown in formation to extend the baseline to ~1 km (see Fig. 2.2). SPECS might have three or more simultaneously illuminated subapertures, providing multiple baselines, and a central beam combining node. The individual subapertures would be somewhat larger than those of SPIRIT. With 4 m mirrors and a total exposure time per field $\sim 10^5$ s (a few days), SPECS would have approximately the same sensitivity to a point source as SPIRIT, but angular resolution comparable to that of the Hubble Space Telescope (HST), the Next Generation Space Telescope (NGST), and the Atacama Large Millimeter Array (ALMA).

Given the requirement to generate high-fidelity images, the SPECS subapertures would have to be moved over a large range of distances. To mitigate the need for a prohibitive amount of thruster propellant, the subaperture spacecraft could be joined with tethers and the whole system spun. Over the exposure period these spacecraft would scan the synthetic aperture plane in a spiral pattern. The subaperture spacecraft could be docked to a central station for repointing. Tethers have never been employed in this manner before. Studies of the dynamics and control of spinning, tethered spacecraft formations are just getting underway.

SPIRIT alone would validate many of the new technologies needed for SPECS (see §3).

3. TECHNOLOGY NEEDS AND CURRENT ACTIVITIES

A number of new technologies are required to enable missions such as SPIRIT and SPECS. We categorize these into the following four general areas: 1) detectors; 2) cooling; 3) optics/interferometry 4) large structures/formation flying.

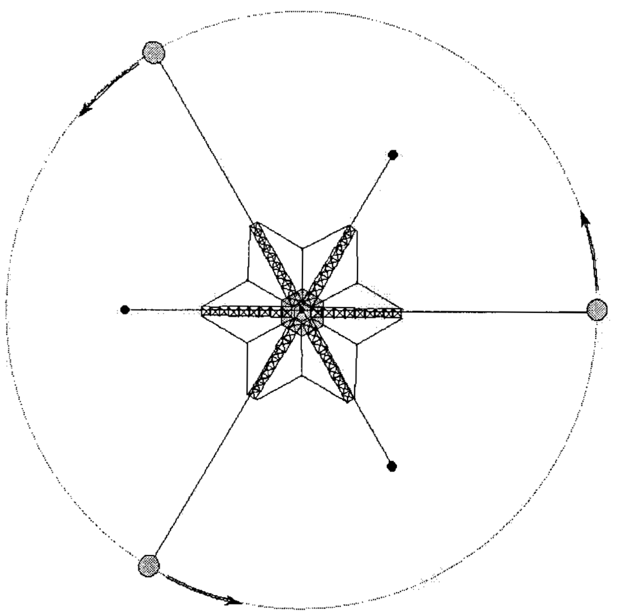

Figure 3. Early concept for SPECS as it would appear from the target of observation. The plane of rotation is perpendicular to the line of sight, minimizing geometric delay. A central hexagonal structure contains the beam combining optics, delay lines, and a capability to obtain short spacing information with additional siderostats that move along the arms to positions close to the center. Tethers join the long baseline light collectors (flat 4m mirrors) to counterweights (or additional mirrors) to reduce spinup as the mirrors are pulled closer to the center. Sun shields would protect all surfaces in the optical path. Note that the central structure resembles SPIRIT, except that it contains three booms instead of one.

3.1. Detectors

There are several detector technologies being developed that may be applicable to the SPIRIT and SPECS missions. The basic goal is a 100×100 photon counting array that can operate in the $40\,\mu$m to $500\,\mu$m wavelength regime. In addition, it may be desirable to have some level of energy discrimination within the detector.

A number of groups are working on bolometers using a voltage biased superconducting transition edge sensor (TES) readout as 2-dimensional arrays. Already, stackable linear arrays of 8 to 32 pixels of TES sensors have been developed by a group from GSFC and NIST. The NEP performance for these arrays is expected to eventually surpass 10^{-18} W Hz$^{-1/2}$. As part of this effort, the NIST team is pioneering the development of the SQUID multiplexer which is critical to reading out multiple pixels.[6] The GSFC team is developing the "pop up detector" (PUD) array structures which allow readout of the TES sensor to occur in the vertical direction thus allowing for thermal isolation and simplifying the multiplexing. At JPL spider web bolometers have been developed with 163 pixel elements[7] (see Fig. 4). This group is currently developing antenna-coupled bolometers combined with planar optics and filters to form integrated imagers and spectrometers. In addition, other teams around the country are developing and proposing alternative array structures for TES detectors. It is expected that array sizes approaching 100×100 with NEP approaching 10^{-19} W Hz$^{-1/2}$ will be available for the SPIRIT mission.

A new detector concept which could enable single photon counting in the FIR from $40\,\mu$m to $500\,\mu$m has been proposed by Schoelkopf et al..[10] This detector, called the Single Quasi-Particle Counter (SQPC), is being developed by a team at Yale University, Goddard Space Flight Center, and the California Institute of Technology. The basic concept of the detector is that photons are absorbed by a superconducting antenna that is coupled to a lower gap aluminum strip. Once in this strip, quasi-particles are confined via Andreev reflection and forced to tunnel through a tunnel junction. The quasi-particles are then read out with an Rf-single electron transistor. The Rf-SETs will be multiplexed in frequency for simplifying readout of multiple pixels. In addition, a single pixel can have several Rf-SETs each tuned to a particular wavelength band set by frequency filters along a strip to to allow for energy discrimination. The predicted NEP of this detector is 3×10^{-20} W Hz$^{-1/2}$. The complete detector has not yet been demonstrated in the lab but is actively being pursued and parts of it have been demonstrated. Eventually, the Rf-SET readout will be multiplexed and thus large arrays (on the order of 100×100) could be developed. It is not yet clear whether a 100×100 version of this detector will be available in time for the SPIRIT mission, but it is hoped that a 100x100 detector with some energy resolution per pixel will be available in time for SPECS.

Also under early conceptual development at GSFC is a FIR/Submm detector capable of photon counting sensitivity. It is called an integrating bolometer, due to its ability to be alternately connected and isolated from its surrounding base temperature. It is read out in a non-dissipate manner using the penetration depth of a supercon-

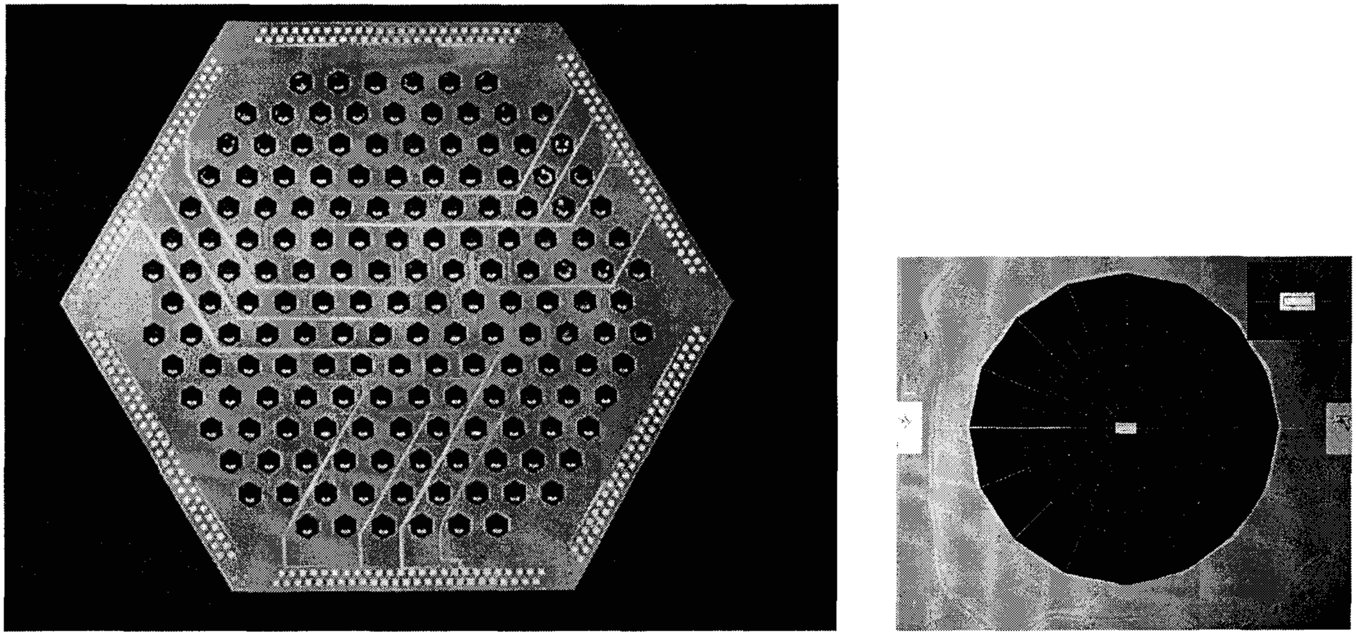

Figure 4. The current state of sub-millimeter direct detector technology are unmultiplexed bolometer arrays. The "spider-web" bolometer array developed for FIRST operates at 350 um with 163 pixels. The bolometers are coupled via an array of conical feedhorns to cover a field of view equivalent to 2600 Nyquist-sampled bare pixels[7] (courtesy of J. Bock, JPL)

ducting film as its thermometer. In continuous operation it will have an NEP of $\lesssim 10^{-21}$ W $\mathrm{Hz}^{-1/2}$. Its configuration allows it to be easily arrayed. This technology could be available in time for SPECS.

3.2. Cooling

Several stages of cooling are required — from the sub-Kelvin temperatures necessary for the detectors, to 4K cooling for the optics, to overall passive cooling of the observatory. More advanced coolers than currently available are necessary to reduce or eliminate the need for cryogens which would limit mission lifetime and increase the mission cost. This must be accomplished with no discernable vibration of the light beams or detectors. We shall address these issues from coldest to warmest.

The basic requirement for cooling the superconducting detectors is the ability to continuously cool the 100×100 arrays to $\lesssim 100$ mK. The expected cooling load at this temperature is up to 10 microwatts. We envision the use of Adiabatic Demagnetization Refrigerators (ADRs). This type of refrigerator has flown on sounding rockets and a flight version was part of the Astro E mission.[11] The key new technology requirements desired for SPIRIT and SPECS are: continuous operation, ability to interface to mechanical coolers both mechanically and in temperature (between 6–10K), and lower mass ($\lesssim 5$ kg).[12] ADRs have extremely high efficiency in these temperature ranges ($> 50\%$) and are extremely well suited for cooling detectors and for extending the mechanical cooler to 4K for actively cooling mirrors.

The second stage of cooling will be performed by active mechanical coolers. Whereas dewar implementations are conceivable, it is highly desirable that the hardware associated with cooling be compact, of low intrinsic mass, and not life-limited. The most promising technologies to cool to 6–10K while remaining within the input power requirements of several 100W, and at the same time have low vibration are the Miniature Reverse Brayton cooler and the Sorption cooler. The former uses a tiny turbine cycling at up to 800,000 RPM. This type of cooler is extremely efficient with predicted performance at up to 10% of Carnot at 10K.[13] At the same time it is essentially vibrationless because the extremely high frequency of operation imparts essentially no energy into the system. This cooler is being developed by Creare Corporation under contract from the Goddard Space Flight Center. A precursor to this cooler using neon at a cooling temperature of 75K has been demonstrated in space. A test using helium as the working fluid has also been conducted in the laboratory. The key remaining technological challenge is the development of a new, smaller turbine allowing it to operate efficiently below 10K.

The other type of cooler that could meet the requirements for mechanical cooling, the Sorption cooler, is being developed for the Planck mission by the Jet Propulsion Laboratory.[14] This type of cooler makes use of the Joule-Thompson cycle, is also vibration free and can be made very small.

Another important technology development for the SPECS and SPIRIT missions is cryogenic, two phase thermal transport devices like the Cryogenic Capillary Pump Loops (CCPL). This technology uses a liquid-vapor phase change and capillary forces to achieve heat transfer with tight temperature control and no moving parts. New thermal transport devices are likely required to connect the active mechanical coolers to the optics, and to the cold spacecraft radiators. In addition to being cold, these devices would likely have to span significant distances, be highly integrated with the structure, and thus include deployable elements. CPL technology is mature at higher working temperatures, but significant development is required to lower the temperature using different working fluids. A GSFC and AFRL team led the space flight demonstration of a CCPL with nitrogen as the working fluid, but the key technological challenge for SPIRIT and SPECS applications would be the ability to use helium (2–5K) and/or neon (25–35K) as the working fluid at low temperatures and for the loops to be flexible to allow deployment and possible motion of the mirrors.

Finally, sunshades will clearly be needed for the SPECS and SPIRIT missions in order to bring the cold side of the observatory down to a temperature at which active cooling of the optical system is feasible. Technology development is required in membrane materials, and deployment systems for sunshades. This technology is being actively pursued for NGST, although it is clear that SPIRIT and SPECS will require a larger distribution of area be shaded and thus larger or more distributed sunshades. At this time, studies for NGST indicate that additional layers of the sunshade would not make a significant improvement in performance but rather conductive coupling of the sunshade to the cold structure is a major driver for performance. Thus, a potentially important area of development is flying the sunshades in formation, although additional studies of the system architecture are needed before the requirements are fully understood. These studies will also dictate whether additional technology development is required in the area of radiators.

3.3. Optics/Interferometry

There are several areas of optics and interferometry that require technology development for the SPECS and SPIRIT missions. Delay lines, and long wavelength beam combination, and a FIR/submm DSM are essential components. As an additional technological challenge these and all other optical components must be cooled to cryogenic temperatures in order to significantly reduce the instrument thermal background. The currently envisioned SPIRIT and SPECS missions require 3-meter class mirrors capable of operating at 4K with approximately 1 μm RMS of wavefront quality. Because of the size and rigidity requirements, conventional mirrors are not able to meet the mass contraints. Even NGST mirrors at 15 kg m^{-2} are likely to contain too much mass. Thus, we propose an areal density goal of 1 kg m^{-2} for flats and 3 kg m^{-2} for powered optics, all capable of being cooled to 4K while maintaining better than 1 μm RMS performance. If necessary, these mirrors can be segmented with little penalty providing they can maintain their relative alignment. Membrane mirrors are also likely candidates; it is anticipated that the SPECS mirrors will be rotating, so the effects of the angular momentum on the figure needs to be taken into account.

Several technologies are being considered for the mirrors. A few examples are the metal membranes being developed by JPL and silicon foam mirrors being developed by a team at Goddard, Schaefer, and Ultramet. Other technologies that could achieve 1 kg m^{-2} flats are expected to be funded through the Gossamer technology NRA due out this spring.

Also important is the development of techniques and algorithms for using interferometry over a wide field of view. To this end, there is a funded effort at the Goddard Space Flight Center to develop a Wide field Imaging Interferometery Testbed (WIIT) that will test out mosaicing techniques for inteferometry over large fields of view (up to 15 arcminutes). This testbed is being developed to run in the visible.

Another critical technology is long stroke cryogenic delay lines for use in Michelson interferometers. JPL is currently developing a long stroke delay line mechanism, but the designs are not specifically directed towards extremely low temperature operation. For SPECS and SPIRIT, the delay lines will need to allow for 4K mirrors and have strokes ranging from several centimeters to perhaps a few meters. For long stroke, this mechanism would likely require a magnetic suspension system (as opposed to conventional bearings or flexures) to eliminate mechanical contact while achieving the desired stroke. Lastly, another important area is beam splitters that can operate at 4K and over the wavelength range from $40\,\mu$m to $500\,\mu$m.

Two major technology development efforts related to SPIRIT are currently underway at JPL. The first of these is to develop cryogenic delay lines and FIR/submm beam combination. The second is to develop metal membrane mirrors (see below). The FIR/submm cryogenic delay line and beam combination effort is structured in three phases. The goal of the first phase is to develop a flexure based, long stroke delay line. Our preliminary designs have a physical travel of approximately 0.25 meters and will accept an input beam of approximately 10 cm diameter. A working model will be built and tested cryogenically. The goal of the second phase is to build a cryogenic FIR/submm submm beam combiner. We are currently evaluating several designs, the simplest of which is a free-standing metal mesh. In the final phase, we will integrate the cryogenic delay line and beam combiner and operate them as a laboratory demonstration FIR/submm interferometer.

At JPL, a fundamentally new technology for constructing large (~10 to 20 meter aperture), low-mass ($\sim 1kg/m^2$) precision reflectors and telescope systems is under development. The technique is simple: cap a rigid volume with a thin, flat, reflective, and stretchable material (the membrane) then pressurize the volume with a gas, similar to inflating a balloon or soap bubble. The shape of the resulting surface is a good approximation to a conic section with higher order polynomial correction terms. If the membrane is stretched beyond its elastic limit, the shape change is permanent resulting in a freestanding reflective surface after the pressure is released. The shape can be modified by changing the boundary, the pressure, or the membrane material. Using the primary reflector in conjunction with adaptable secondary and tertiary reflectors, wavefront distortion may be corrected, resulting in a diffraction limited telescope system. A freestanding membrane suitable for use as a reflector at far-IR/submillimeter wavelengths has been demonstrated.[15]

In addition, we have submitted proposals to develop a cryogenic FIR/submm DSM and advanced ADR and heat switch technologies. The near term goal of the JPL technology development effort is to build a FIR/submm prototype interferometer. This instrument would be used as a testbed for out technology development efforts. It would also serve to demonstrate the technology development results by making astronomical observations from a remote site or from a balloon.

3.4. Large structures/Formation flying

The requirements for SPIRIT in the area of large structures is driven mostly by the need for low mass, deployable, cryogenic truss structures that can be integrated with the cooling system to maintain mirrors at 4K. Depending on the final SPIRIT configuration, this deployed structure will have to either be controllable in length, utilize multiple subaperture flats as outlined in §2.1, or house tracks and a mechanism for moving mirrors along its length. For SPECS and particularly for SPIRIT, this system will also have to be relatively quiet and precise, and may require active shape and damping control. While it may be possible to modify existing technology, advances in low mass, deployable trusses extending 20 meters and capable of cryogenic operation are greatly desired, in addition to technologies related to controlling the baseline by moving the collecting mirrors.

In order to sample a large portion of the u-v plane with baselines up to ~1 km, new technology is needed to avoid requiring ultra-large metering structures, or excessive amounts of propellant for formation flying. One method that has been proposed by the SPECS team at GSFC is to use tethers and formation flying together, to form a large baseline observatory that maintains symmetry while rotating.[16] This allows for balanced deployment and retraction of the system (collecting mirrors), and stabilizing centripetal forces which keep the tethers taught. This tethered formation can be used to position and control the mirrors at fixed or varying relative positions, changing baseline and synthetically filling the effective large aperture. In order to understand whether this can be done, new types of models need to be developed that combine the tether dynamics, with the various nested observatory control systems (tether deployment control, delay line control, and formation flying control). Initial work in this area has begun at the Goddard Space Flight Center. As a result of this modeling effort, requirements for the tethers and formation flying will be better understood.

While many challenges exist to enable the SPECS and SPIRIT missions, there are solutions to each of these challenges that appear solvable with time and money. In addition, many of these technology areas overlap with nearer term missions and thus will have to be solved well before SPIRIT and SPECS become a reality. Thus, a final and critical consideration is to make certain there is sufficient continuity to assure these technologies are not only developed but also available for SPIRIT and SPECS.

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